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August 1, 1987 to January 31, 1990.

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**HIGH PERFORMANCE HOLOGRAPHIC  
ELEMENTS AND MEDIA**

December 1989

**Nicholas George  
Principal Investigator**

**The Institute of Optics  
University of Rochester  
Rochester, New York**

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Research in the field of holographic optical elements is summarized for the contract period of August 1, 1987 to January 31, 1990. The basic understanding of structure and mechanism of a high performance holographic photopolymer has been extended. Further, novel holographic elements and systems based on these elements have been devised. Discussion of these results is presented.			
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# HIGH PERFORMANCE HOLOGRAPHIC ELEMENTS AND MEDIA

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# **HIGH PERFORMANCE HOLOGRAPHIC ELEMENTS AND MEDIA**

## **I. INTRODUCTION**

This report contains a description of the basic research activities of the Principal Investigator, Dr. Nicholas George, Professor of Optics, and Dr. Thomas W. Stone, Scientist in Optics, at the University of Rochester, under Contract No. DAAL03-87-K-0100. The period covered is August 1, 1987 to January 31, 1990. The Scientific Program Manager was Dr. B. D. Guenther.

## **II. LISTING OF RESEARCH TOPICS**

Several different topics of investigation were reported. Results on this research were reported in the published literature as reviewed in Section III. In addition, important results of a technical nature were related in memoranda to Mark Norton of the U.S. Army CECOM Center for Night Vision and Electro-Optics; and to Dr. B. D. Guenther of the U.S. Army Research Office. Further, a report on the subject of novel holographic elements for wavelength sensing was presented in a briefing by Dr. T. Stone to the Defense Advanced Research Projects Agency.

Studies can be grouped in the topic areas that are listed below:

- A. DMP-128 Recording Material
- B. Video Diffractometer
- C. Hybrid Refractive-Diffractive Elements
- D. Achromatic Phase Modulator
- E. White Light Phase Conjugation
- F. Active Hologram Devices
- G. Non-Silver Black-and-White and Color Photographic Medium
- H. Novel Holographic Elements for Wavelength Sensing
  - I. Secure Communications
  - J. Hybrid Telescope

### III. ABSTRACTS FROM PUBLICATIONS AND PRESENTATIONS

#### HYBRID SINGLET ARBITRARILY DISPERSIVE ELEMENT

Thomas Stone and Nicholas George  
The Institute of Optics  
University of Rochester  
Rochester, New York 14627

#### ABSTRACT

Hybrid elements containing optical power with both diffractive (holographic) and refractive components are shown to be useful for obtaining arbitrary, or in a special case, achromatic, dispersive characteristics. In one configuration a volume holographic element is coated on the surface of a crown glass lens, and by varying the power distributions among the refractive and holographic components while maintaining constant overall optical power the effective Abbe  $V$ -numbers of the resultant hybrid element are shown to span all real numbers except a narrow interval around zero.

In the case of the achromat ( $V$ -number =  $\infty$ ), both refractive and diffractive components are of the same sign resulting in smaller glass curvatures than in all-refractive achromat doublets. Applications are expected to include chromatic aberration correlator plates in high-performance optical systems. Such correlator plates may have any net power (including zero) while exhibiting effective  $V$  numbers that are positive or negative and that span a wide range, e.g.,  $\pm 1$  or  $\pm 1000$ . Further advantages include reducing the need for choosing high-dispersion glasses which may be costly and difficult to grind or polish. High-diffraction efficiency and broad spectral bandwidths (in excess of 300 nm) are obtained in the holographic optical elements using single-element central stop and cascaded element designs.

Experimental measurements are given in support of the theoretical predictions.

Presented at the 1987 Optical Society of America Meeting, Rochester, New York, October 18-23, 1987.

# ACHROMATIC PHASE SHIFTER OR MODULATOR

Nicholas George and Thomas Stone  
The Institute of Optics  
University of Rochester  
Rochester, New York 14627

## ABSTRACT

Achromatic optical systems forming phase shifters and phase modulators are presented and shown to impart phase angle shifts in incoming waves which are independent of wavelength over extremely broad spectral ranges. Three major classes of achromatic phase shifter are described including the triangle, close cascade, and imaged grating configurations. When constructed utilizing volume holographic optical elements, very high diffraction efficiencies may be achieved over the large bandwidths used. These systems may similarly be utilized to impart achromatic frequency shifts and frequency modulations which are wavelength independent over extreme spectral ranges and usually do not disturb the spatial form of the input waves. These devices may be used in AC interferometers and allow such interferometers to be operated in white light. Achromatic phase shifts of  $0, +\phi, -\phi, +2\phi, -2\phi, \dots$ , may be simultaneously obtained.

Experimental results are presented in support of the discussion.

Presented at the 1987 Optical Society of America Meeting, Rochester, New York, October 18-23, 1987. A patent has been issued on this device, see Pg. 14 of this report.

# **ACHROMATIZED HOLOGRAPHIC PHASE SHIFTER AND MODULATOR**

**Nicholas George and Thomas Stone  
The Institute of Optics  
University of Rochester  
Rochester, New York 14627**

## **ABSTRACT**

**Novel achromatic optical systems forming phase shifters and phase modulators are presented and shown to produce phase-angle shifts in incoming waves which are independent of wavelength over broad spectral ranges. Three achromatic phase shifters are described including the triangular, close cascade, and imaged grating configurations. Applications are discussed and experimental results are given in support of the theory.**

**Opt. Comm. 67, 185-191 (1988).**



# **WHITE LIGHT INTERFEROMETRY WITH AN ACHROMATIC PHASE SHIFTER**

**Nicholas George and Thomas Stone  
The Institute of Optics  
University of Rochester  
Rochester, New York 14627**

## **ABSTRACT**

The principle of operation of an achromatic modulator or phase shifter is presented. Specific triangular configurations are described that consist of two base gratings and a vertex element which may be either a transmission-type hologram or an acousto-optic modulator. The application of this concept is illustrated by a generalized white light interferometer with very fine differential phase control and two separated, colinear output paths. The achromatic phase shifter is also shown to make an important improvement to the white light cosinusoidal transform hybrid. Two different configurations are presented.

Proc. Soc. Photo-Opt. Instr. Eng. **883**, 196-202 (1988).

# HYBRID DIFFRACTIVE-REFRACTIVE LENSES AND ACHROMATS

Thomas Stone and Nicholas George  
The Institute of Optics  
University of Rochester  
Rochester, New York 14627

## ABSTRACT

Hybrid elements containing optical power with both diffractive (holographic) and refractive components are shown to be useful for obtaining arbitrary or, in special cases, achromatic dispersive characteristics. In one configuration a volume holographic element is coated on the surface of a crown glass lens, and by varying the power distributions among the refractive and holographic components while maintaining constant overall optical power the effective Abbe  $V$ -numbers of the resultant hybrid element are shown to span all real numbers excepting a narrow interval around zero. In the achromat case ( $V$ -number =  $\infty$ ), both refractive and diffractive components are of the same sign resulting in much smaller glass curvatures than in all-refractive achromat doublets or apochromat triplets. The large separation between holographic partial dispersions and available glass partial dispersions is shown to lead to hybrid three-color achromats with greatly reduced glass curvatures. Applications are expected to include broadband achromatic objectives and chromatic aberration corrector plates in high performance optical systems. Such corrector plates may have any net power (including zero) while exhibiting effective  $V$  numbers that are positive or negative and that span a wide range, e.g.,  $\pm 1$  or  $\pm 1000$ . Further advantages include reducing the need for choosing high dispersion glasses, which may be costly and difficult to grind or polish. High diffractive efficiency and broad spectral bandwidths (in excess of 3000 Å) are obtained in the holographic optical elements using single-element central-stop and cascaded element designs.

Applied Optics 27, 2960-2971 (1988).

# **CHROMATIC AND SPHERICAL ABERRATIONS IN HOLOGRAPHIC AND HYBRID LENSES**

Thomas Stone and Nicholas George  
The Institute of Optics  
University of Rochester  
Rochester, New York 14627

## **ABSTRACT**

Longitudinal-chromatic and -spherical aberration, and lateral color are considered in various all holographic and hybrid diffractive/refractive lenses. These lenses include hybrid objectives,<sup>1</sup> dialytes, and separated configurations. Raytracing and first-order analytic approaches are used in this analysis. Two-element hybrid dialytes are described which eliminate lateral or longitudinal chromatic aberrations. Applications of curved-holographic elements in simultaneously reducing both aberrations are discussed. A unique volume hologram aberration is discussed which is present even paraxially and is dependent only on wavelength change and element thickness. Low scatter holograms have also been fabricated to illustrate some of these principles and to demonstrate the high quality performance attainable.

<sup>1</sup>Thomas Stone and Nicholas George, "Hybrid diffractive-refractive achromats and lenses," Appl. Opt. 27, 2960-2971 (1988).

Presented at the 1988 Optical Society of America Meeting, Santa Clara, California, October 31-November 4, 1988.

**STRUCTURAL AND OPTICAL PROPERTIES OF  
DMP-128 HOLOGRAMS DURING ENVIRONMENTAL TESTING**

M. Troll and J. Formosa  
Polaroid Corporation  
750 Main Street  
Cambridge, MA 02139

**ABSTRACT**

Changes in the structure of photopolymer holograms during environmental testing were studied with two techniques: (1) scanning electron microscopy of freeze-fracture cross-sections and (2) modeling the refractive index profile. The profile was estimated using optical data: reflectivities corresponding to the fundamental spatial frequency and the second harmonic. We chose to use holograms that had not been through the normal stabilization treatments for the material, in order to study the properties of the basic structure. The changes are interpreted within the context of the void model for this photopolymer's structure.

Proc. Soc. Photo-Opt. Instr. Eng. **1051**, 90-95 (1989).

# **INDEX VARIATION AND SCATTERING IN A HOLOGRAPHIC MEDIUM**

**Thomas Stone, Nicholas George, and B. D. Guenther\***

**The Institute of Optics  
University of Rochester  
Rochester, New York 14627**

**\*Physics Division  
U.S. Army Research Office  
Research Triangle Park, NC 27709**

## **ABSTRACT**

In the fabrication of holographic optical elements, it is important to have careful characterization of the recording medium. Hence, we have made measurements of the increment in the index of refractions vs. exposure for DMP-128 manufactured by Polaroid Corporation. The results of measurements are presented for a series of holographic diffraction gratings. A novel spectrophotometer technique that provides a simultaneous measure of both thickness and refractive index is described. Data illustrating its use are presented for the holographic photopolymer. The feasibility of filling voids in the processed photopolymer for device applications was demonstrated by construction of a distributed feedback dye laser in a DMP-128 grating. At high spatial frequencies, diffraction efficiency is used to estimate refractive index variations. As an initial finding, we report a rather large modulation in the index of refraction of 0.2 at 1000 cycles/mm.

Proc. Soc. Photo-Opt. Instr. Eng. **1136**, 35-44 (1989).

# **SENSITOMETRY AND SCATTERING CHARACTERISTICS OF A HOLOGRAPHIC PHOTOPOLYMER**

Thomas Stone and Nicholas George  
The Institute of Optics  
University of Rochester  
Rochester, NY 14627

## **ABSTRACT**

Basic sensitometry and scattering characteristics are presented for the DMP-128 holographic photopolymer manufactured by Polaroid Corporation. The refractive index modulation is studied as a function of exposure for a variety of spatial frequencies (0, 10, 100, 1000, 5000 mm<sup>-1</sup>). DMP-128 is capable of very large refractive index modulations, on the order of 0.2, at high spatial frequencies. Scanning electron micrographs reveal a globular microstructure consisting of balls with diameter on the order of 0.04 - 0.1  $\mu\text{m}$ , and these balls give rise to index modulation as a result of variations in their packing density. The appearance of these scanning electron micrographs is very similar to those of sol-gel glasses. Performance characteristics of a wavelength-scanning technique for simultaneously measuring the average bulk refractive index as well as the thickness and loss constant of a thin-film emulsion or photopolymer coating are presented in detail. At high spatial frequencies diffraction efficiency is used to estimate refractive index variations by comparison with a thin grating decomposition model. Another aspect of this investigation is the scattering level of the microscopic index inhomogeneities that comprise the recording. Using a wide-angle scatterometer devised for such measurements, we have observed very low scattering in photopolymer gratings.

Presented at the 1989 Optical Society of America Meeting, Orlando, Florida, October 15-20, 1989.

#### **IV. LISTING OF PUBLICATIONS**

##### **A. Manuscripts/Publications**

1. "Achromatized holographic phase shifter and modulator," Nicholas George and Thomas Stone, *Opt. Comm.* **67**, 185-191 (1988).
2. "White light interferometry with an achromatic phase shifter," Nicholas George and Thomas Stone, *Proc. Soc. Photo-Opt. Instr. Eng.* **883**, 196-202 (1988).
3. "Hybrid diffractive-refractive lenses and achromats," Thomas Stone and Nicholas George, *Appl. Opt.* **27**, 2960-2971 (1988).
4. "Structural and optical properties of DMP-128 holograms during environmental testing," M. Troll and J. Formosa, *Proc. Soc. Photo-Opt. Instr. Eng.* **1051**, 90-95 (1989). Publication by Polaroid Corporation under subcontract.
5. "Index variation and scattering in a holographic medium," T. Stone, N. George, and B. D. Guenther, *Proc. Soc. Photo-Opt. Instr. Eng.* **1136**, 35-44 (1989).

##### **B. Abstracts/Presentations**

1. "Hybrid 'singlet' arbitrarily dispersive element," Thomas Stone and Nicholas George, presented at the 1987 Optical Society of America Meeting, Rochester, NY, October 1987.
2. "Achromatic phase shifter or modulator," Thomas Stone and Nicholas George, presented at the 1987 Optical Society of America Meeting, Rochester, NY, October 1987.
3. "Chromatic and spherical aberrations in holographic and hybrid lenses," Thomas Stone and Nicholas George, presented at the 1988 Optical Society of America Meeting, Santa Clara, CA, November, 1988.
4. "Structural and optical properties of DMP-128 holograms during environmental testing," M. Troll and J. Formosa, presented at Proc. Soc. Photo-Opt. Instr. Eng. Meeting, Los Angeles, CA, January 1989. Publication by Polaroid Corporation under subcontract.
5. "Index variation and scattering in a holographic medium," T. Stone, N. George, and B. D. Guenther, presented at Europtica-Services I.C. Meeting, Paris, France, May, 1989.
6. "Sensitometry and scattering characteristics of a holographic photopolymer," T. Stone and N. George, presented at the 1989 Optical Society of America Meeting, Orlando, FL, October 1989.

#### **IV. LISTING OF PUBLICATIONS (continued)**

##### **C. Video Presentation for NVEOC**

**"Laser Video Diffractometer," (10 minute)**

A field demonstration of the video diffractometer using red and green lasers. Several copies of this film were sent to NVEOC on 3/4 inch format.



## **V. LISTING OF INVENTIONS DISCLOSED**

### **A. List of inventions with patents granted under ARO sponsorship (initial filing may have been under an earlier ARO contract):**

1. "Optical systems utilizing a volume transmission diffraction element to provide wavelength tuning"  
Inventors: Nicholas George and Thomas W. Stone  
Patent No. 4,752,130, granted June 21, 1988
2. "Broad-spectrum achromatic phase shifters, phase modulators, frequency shifters, and frequency modulators"  
Inventors: Thomas W. Stone and Nicholas George  
Patent No. 4,786,124, granted November 22, 1988
3. "Optical systems using volume holographic elements to provide arbitrary space-time characteristics, including frequency-and/or spatially-dependent delay lines, chirped pulse compressors, pulse chirpers, pulse shapers, and laser resonators"  
Inventors: Nicholas George and Thomas W. Stone  
Patent No. 4,834,474, granted May 30, 1989

### **B. Disclosures made:**

1. "Active hologram devices: distributed feedback and distributed gain hologram lasers"  
Inventors: T. Stone and N. George  
Disclosed September 23, 1988
2. "Non-silver black-and-white color photographic process and color holographic technique"  
Inventors: T. Stone and N. George  
Disclosed September 23, 1988
3. "White light phase conjugators"  
Inventors: T. Stone and N. George  
Disclosed September 23, 1988
4. "Optical device for secure communications"  
Inventors: T. Stone and N. George  
Disclosed September 23, 1988

## **VI. SCIENTIFIC PERSONNEL**

Personnel at the University of Rochester were:

Dr. Nicholas George, Principal Investigator  
Dr. Thomas W. Stone, Co-Investigator  
Brian McIntyre, Electron Microscopy  
John Hall, Research Assistant  
Eugene Zhang, Research Assistant